Overview of kaon physics

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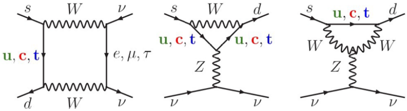
Outline

- **Golden modes of kaon physics:**
  - $K^+ \to \pi^+ \nu \bar{\nu}$ @NA62 experiment, CERN
  - $K_L \to \pi^0 \nu \bar{\nu}$ @KOTO experiment, J-PARC
  - $K_S \to \mu^+ \mu^-$ @LHCb, CERN

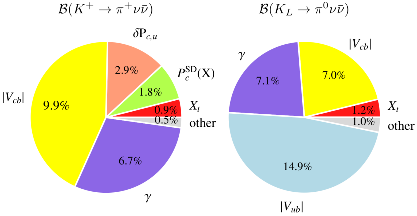
- **Other Kaon physics at NA62 experiment**
  - Precision measurement of $K^+ \to \pi^+ \mu^+ \mu^-$ decay
  - Recent results on χPT studies
  - LFUV, LFV, LNV studies
  - New results on dark sector studies with kaon decays

- **Future of kaon physics at the CERN SPS**
  - Two more years of data-taking for **NA62** experiment
  - **HIKE** project under discussion at CERN: rich program with K^+, K_L beams, dark sector searches

- **FCNC loop process**
  - s $\to$ d **coupling** and highest CKM suppression (BR$\sim |V_{ts} \times V_{td}|^2$)



- **Very clean theoretically**
  - Short distance contribution and no hadronic uncertainties
  - Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
  - Theoretical error budget dominated by CKM parameters



- **SM predictions**

[Buras et al., JHEP 1511 (2015) 033]

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

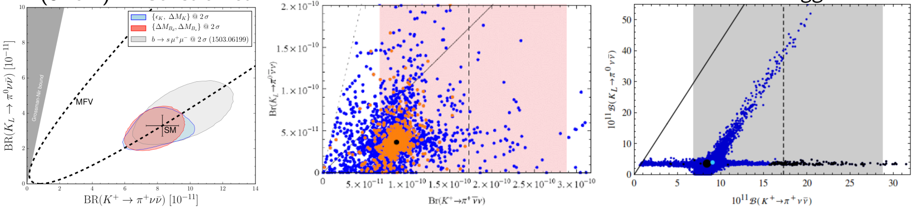
$$\mathrm{BR}(K_L^0 \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6) \cdot 10^{-11}$$

$K \to \pi\nu\bar{\nu}$: *Theoretical motivation - Beyond the SM*

- Simplified Z, Z' models *[Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]*
- Littlest Higgs with T-parity *[Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]*
- Custodial Randall-Sundrum *[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]*
- MSSM non-MFV *[Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162; Isidori et al. JHEP 0608 (2006) 064]*
- LFU violation models *[Isidori et. al., Eur. Phys. J. C (2017) 77]*
- Leptoquarks *[S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]*

- Constraints from existing measurements (correlations model dependent):
  Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches
- $K \to \pi\nu\bar{\nu}$ **can discriminate among different new physics scenarios**

$Z'(5\,TeV)$ *in ConstrainedMFV* — *Randall – Sundrum* — *LittlestHiggs*

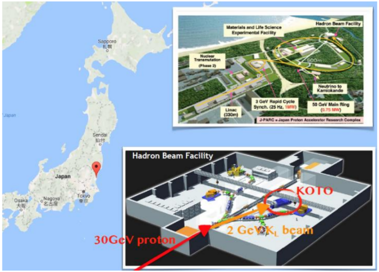


The KOTO Experiment

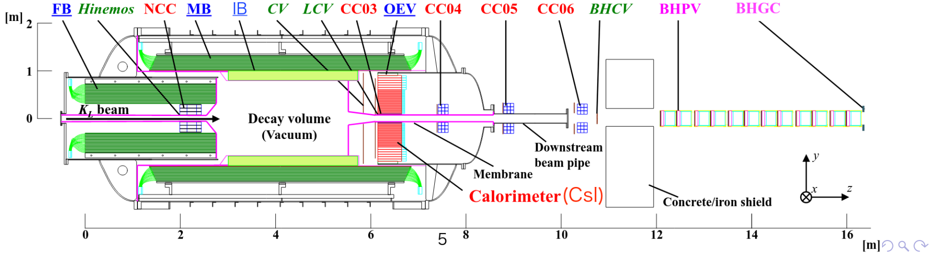
Study of $K_L \to \pi^0 \nu \bar{\nu}$ @JPARC 30 GeV Main Ring

Goal is to search for New Physics at $BR \sim 10^{-11}$

- Primary 30 GeV/c protons on gold target
- Secondary neutral beam (K_L, neutrons, photons)
- P = 1.4 GeV/c peak
- Transverse size: 80×80 mm^2
- Fiducial decay region ~ 2 m



Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata



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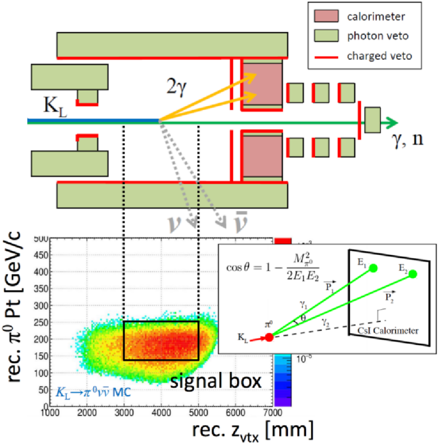
$K_L \to \pi^0 \nu \bar{\nu}$:

- 2γ with high P_T = signal
- K_L momentum not known $\to$ Kinematics with p_T
- Decay vertex reconstructed assuming $M_{\gamma\gamma} = m_{\pi^0}$

Hermetic Detector

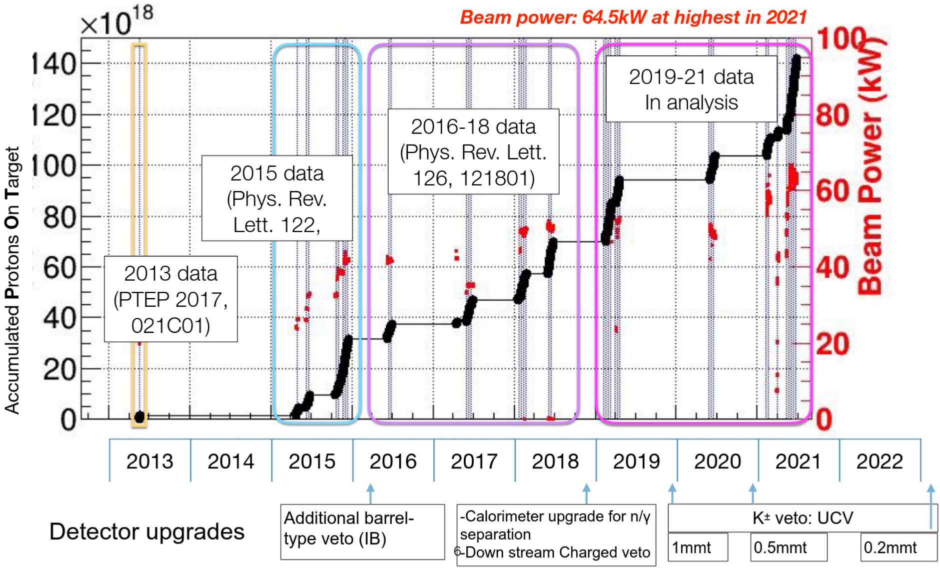
- no signal in veto detectors



Backgrounds from K_L decays

Decay mode	BR [%]	Rejection tools
$K_L \to \pi^\pm e^\mp \nu$	40.6	charged, non-EM
$K_L \to \pi^\pm \mu^\mp \nu$	27.0	charged, non-EM
$K_L \to \pi^+ \pi^- \pi^0$	12.5	charged, low π^0 P_T
$K_L \to \pi^0 \pi^0 \pi^0$	19.5	extra γ
$K_L \to \gamma\gamma$	$5.5 \cdot 10^{-4}$	low P_T, symmetry
$K_L \to \pi^+ \pi^-$	$2.0 \cdot 10^{-3}$	charged, non-EM
$K_L \to \pi^0 \pi^0$	$8.6 \cdot 10^{-4}$	extra γ

Data accumulation history



Expected $K_L \to \pi^0 \nu\bar{\nu}$ from SM:

- 0.04 events

Predicted backgrounds:

- 1.22 ± 0.26 events

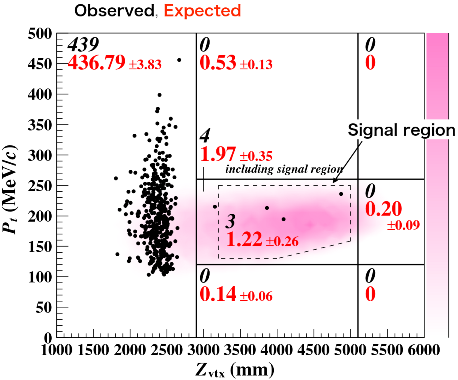
Observed in the signal region:

- 3 events

Final result:

- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ @90% C.L.

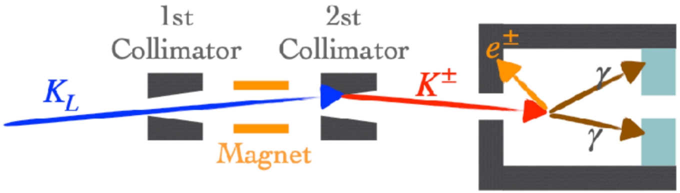
[PRL 126 (2021) 121801]



Backgrounds table

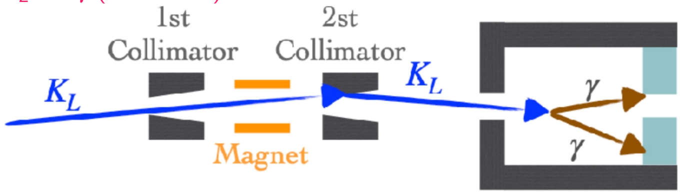
Process	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07
Other K_L decays	0.005 ± 0.005
$K^\pm$ ($K_{e3}, K_{2\pi}, K_{\mu 3}$)	0.87 ± 0.25
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
Total	1.22 ± 0.26

$K^{\pm}$ background : $K^{\pm} \to \pi^0 e^{\pm} \nu$



- Installed Upstream Charged Veto (UCV, in 2021) for $K^{\pm}$ detection
- Reduced by a factor of 13 with 97% signal efficiency.

$K_L \to 2\gamma$ (beam halo):



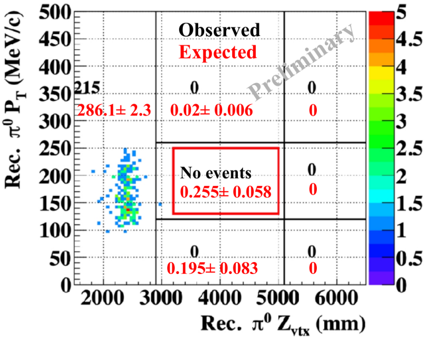
- Developed a likelihood ratio cut based on shower shape and a Multi variable analysis cut based on kinematical variables
- Reduced by a factor of 8 with 94% signal efficiency

Focus on the analysis of 2021 data because the background level is smallest in this data set thanks to (UCV) newly installed in 2021

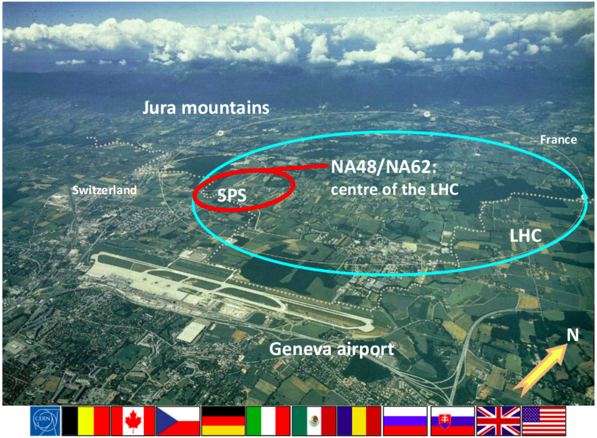
- Key points on the 2021 data analysis
  - Implemented measures to reduce the $K^{\pm}$ and Halo $K_L \to 2\gamma$ BG
  - $K^{\pm}$, $K_L \to 2\gamma$ backgrounds $< \mathcal{O}(0.1)$
  - Developed several analysis methods to estimate BG events more accurately

Backgrounds table - preliminary

Source	Current estimation
Upstream π^0	$0.064 \pm 0.005_{stat} \pm 0.006_{sys}$
$K_L \to 2\pi^0$	$0.060 \pm 0.022_{stat} (^{+0.051}_{-0.060})_{sys}$
$K^{\pm}$	$0.043 \pm 0.015_{stat} (^{+0.004}_{-0.030})_{sys}$
Hadron cluster	$0.024 \pm 0.004_{stat} \pm 0.006_{sys}$
Scattered $K_L \to 2\gamma$	$0.022 \pm 0.005_{stat} \pm 0.004_{sys}$
Halo $K_L \to 2\gamma$	$0.018 \pm 0.007_{stat} \pm 0.004_{sys}$
CV η	$0.023 \pm 0.010_{stat} \pm 0.006_{sys}$
Total	$0.255 \pm 0.058_{stat} (^{+0.053}_{-0.068})_{sys}$



$BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.0 \times 10^{-9}$ (90% CL)



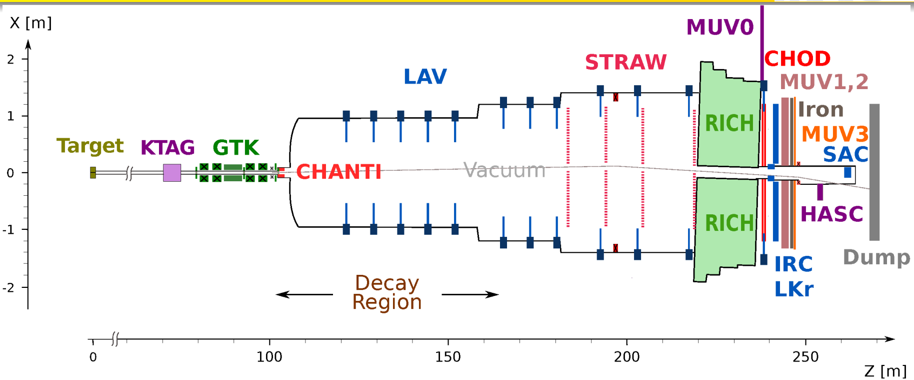
Kaon decay in flight experiments.

NA62: ~300 participants, ~ 30 institutes

Earlier: NA31

NA48 discovery of direct CPV	1997	ε'/ε: K_L+K_S	
	1998	K_L+K_S	
	1999	K_L+K_S	K_S HI
	2000	K_L only	K_S HI
	2001	K_L+K_S	K_S HI
NA48/1	2002	K_S/hyperons	
NA48/2	2003	K^+/K^-	
	2004	K^+/K^-	
NA62 R_K phase	2007	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
	2008	$K^\pm_{e2}/K^\pm_{\mu 2}$	tests
NA62	2014	pilot run	
	2015	commissioning run	
	2016 – 18	$K^+ \to \pi^+ \nu\nu$ run	
	2021 – 23	$K^+ \to \pi^+ \nu\nu$ run	

NA62 Detector layout



SPS Beam:

- 400 GeV/c protons
- 1.9×10^{12} p/spill
- 3.5 s spill
- $\sim 10^{18}$ POT/year

Secondary beam:

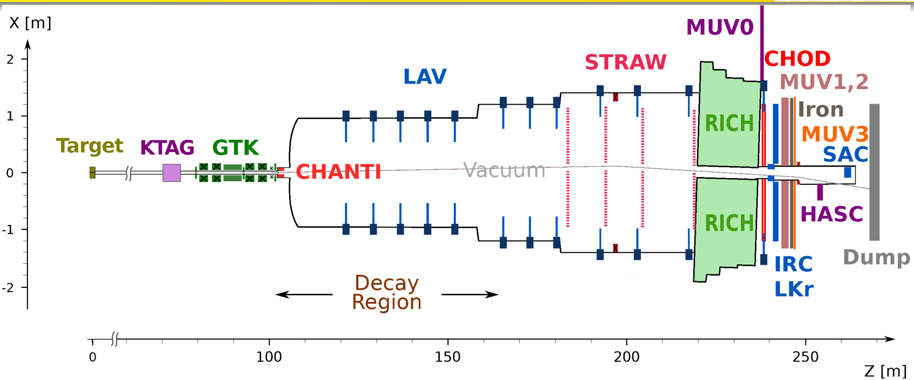
- 75 GeV/c momentum, 1% RMS
- 100 μrad divergence (RMS)
- 60×30 mm^2 transverse size
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 450 MHz of particles at GTK3

Decay Region

- 60 m long fiducial region
- ~ 3 MHz K^+ decay rate
- Vacuum $\mathcal{O}(10^{-6})$ mbar

[The NA62 Collaboration, JINST 12 (2017) P05025]

NA62 Detector layout



Upstream detectors (K^+)

- **KTAG:** differential Cherenkov counter for K^+ ID
- **GTK:** Si pixel beam tracker
- **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions

[The NA62 Collaboration, JINST 12 (2017) P05025]

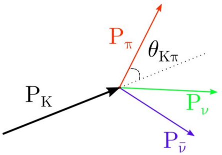
Downstream detectors (π^+)

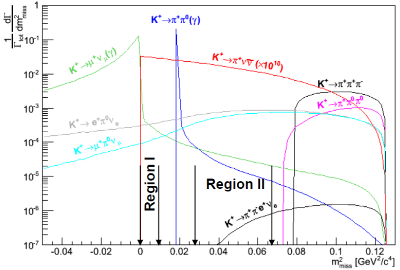
- **STRAW:** track momentum spectrometer
- **CHOD:** scintillator hodoscopes
- **LKr/MUV1/MUV2:** Calorimeters
- **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
- **LAV/SAC/IRC:** Photon veto detectors
- **MUV3:** Muon detector

$K^+ \to \pi^+ \nu \bar{\nu}$: Analysis strategy

Kaon decays in flight

- **Signal:** Time and space $K^+ - \pi^+$ matching
- **Regions defined by:** $m^2_{miss} = (P_K - P_\pi)^2$
- The analysis is mostly cut based
- **Blind analysis:** Signal and background ctrl regions are kept blind throughout the analysis





Main background sources

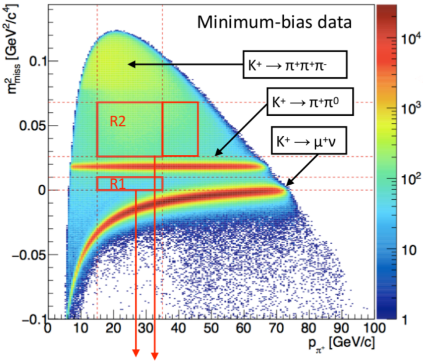
Decay mode	BR	Main rejection tools
$K^+ \to \mu^+ \nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+ \pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	6%	multi + kinematics
$K^+ \to \pi^+ \pi^0 \pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+ \nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%	μ–ID + γ-veto

Requirements

- $\mathcal{O}(100)$ ps timing between sub-detectors
- $\mathcal{O}(10^4)$ background suppression with kinematics
- $\mathcal{O}(10^7)$ μ-suppression ($K^+ \to \mu^+ \nu$)
- $> (10^7)$ π^0-suppression ($K^+ \to \pi^+ \pi^0$,$\pi^0 \to \gamma\gamma$)

Signal regions

- Three different ways to calculate m_{miss} to avoid mis-reconstruction:
  - $m^2_{miss} = (STRAW,\ GTK)$
  - $m^2_{miss} = (RICH,\ GTK)$
  - $m^2_{miss} = (STRAW,\ Beam)$



Kinematic cuts to define signal regions R1 and R2

Selection

- Single track in final state topology matched with upstream K^+
- π^+ identification
- Photon rejection
- Multi-track rejection
- $105 < Z_{vertex} < 165$ m
- $15 < P_{\pi^+} < 35$ GeV$/c$ in R1
  $15 < P_{\pi^+} < 45$ GeV$/c$ in R2
  (best μ/π discrimination in RICH & to leave at least 30 GeV of E_{miss})

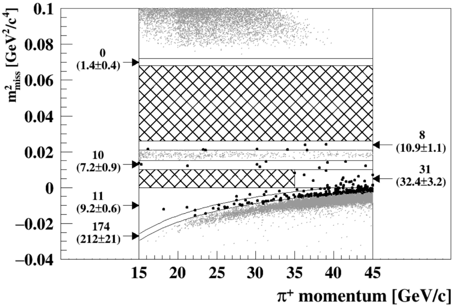
Performance

- $\varepsilon(\mu) = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon(\pi^0) = (1.4 \pm 0.1) \cdot 10^{-8}$
- $\sigma(m_{miss}) = 1 \cdot 10^{-3}$ GeV$^2/c^4$
- $\sigma(t) \sim \mathcal{O}(100)$ ps

$K^+ \to \pi^+ \nu\bar{\nu}$: Background

Background expectation validated using control regions.

Observed (expected) events in control regions. Signal Regions are masked!



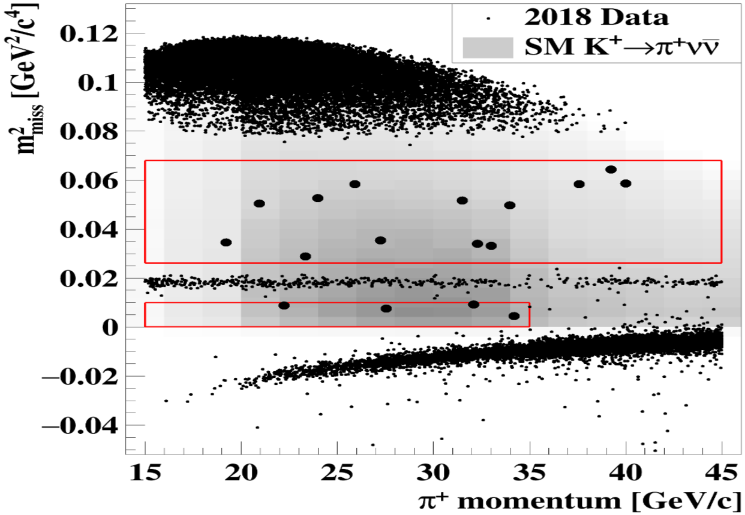
Validation: expected vs observed background events
in control regions in bins of π^+ momentum

In 2018 collimator was replaced to remove early decays mechanism and data are split in subsets S1/S2 ($\sim$ 20%/80% of 2018 data).
It allows to relax some cuts for S2,
while keeping the S/B ratio same as for S1.

Background	Subset S1	Subset S2
$\mu^+\nu$	0.23 ± 0.02	0.52 ± 0.05
$\pi^+\pi^0$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^- e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0\ell^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Background estimates summed over Region 1 and Region 2

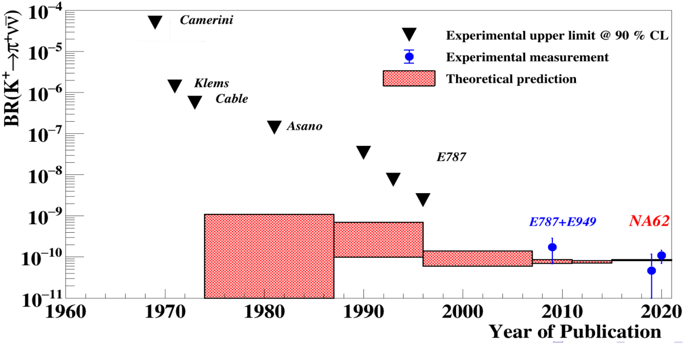
17 events observed in signal region



$BR(K^+ \to \pi^+ \nu\bar{\nu})$ at NA62: Result

	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^2$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
Observed events	1	2	2	15
	[PLB 791 (2019) 156-166]	[JHEP 11 (2020) 042]	[JHEP 06 (2021) 093]	

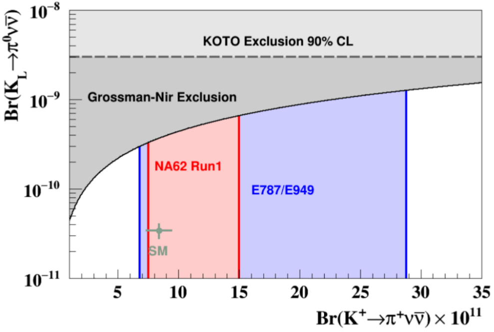
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ **(3.4σ significance)**

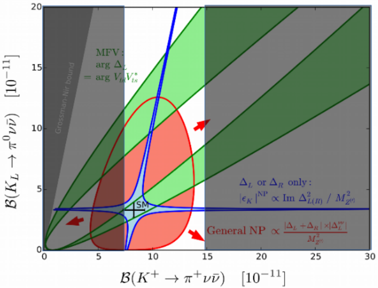


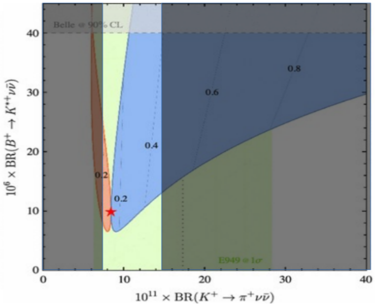
Interpretation of result

Large deviations from SM BR($K^+ \to \pi^+ \nu\bar{\nu}$) are excluded

$\to$ high precision measurement needed





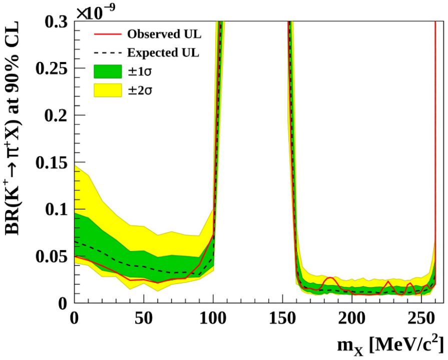


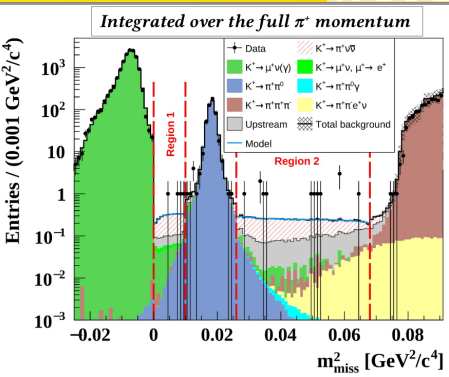
Grossman-Nir limit:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 4.3 \cdot BR(K_L \to \pi^0 \nu\bar{\nu})$

[Phys. Lett. B 398, 163 (1997)]

Search for $K^+ \to \pi^+ X(invisible)$



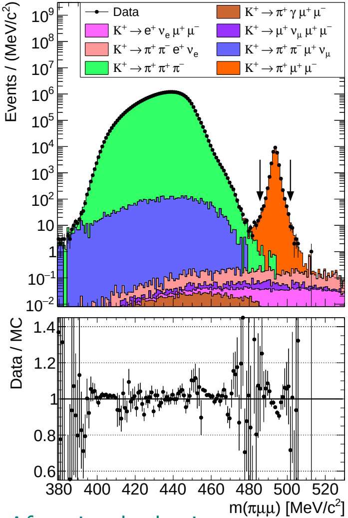


- Search for X particle production in $K^+ \to \pi^+ X$ decays
- Technique: peak searching using the m^2_{miss} observable for m_X in the 0-260 MeV$/c^2$ range
- Background shapes taken from the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis including the shape of the SM $K^+ \to \pi^+ \nu\bar{\nu}$ process itself
- 90% Upper limits on BR$(K^+ \to \pi^+ X)$ in $(10^{-11} - 10^{-10})$ range

[JHEP 06 (2021) 093]

$K^+ \to \pi^+\mu^+\mu^-$: *Precision measurement*

- Heavily suppressed FCNC transition: $s \to d\ell^+\ell^-$
- Main kinematic variable: $z = \frac{m^2(\ell^+\ell^-)}{m_K^2}$
- Form Factor of the $K^\pm \to \pi^\pm\gamma^*$ transition: $W(z)$
- Chiral Perturbation Theory (ChPT) parametrization of $W(z)$ at $\mathcal{O}(p^6)$:
  - $W(z) = G_F m_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$
- Main goals of the $K^+ \to \pi^+\mu^+\mu^-$ measurement:
  - Model-independent measurement of the $B_{\pi\mu\mu}$ branching fraction
  - Measure the function $|W(z)|^2$
  - Determine the Form Factor parameters a_+ and b_+: LU predicts same a, b for e, μ
  - Forward - backward asymmetry: Asymmetries in angular distribution could point to NP contributions



After signal selection:

$N_{obs} = 27679$ events

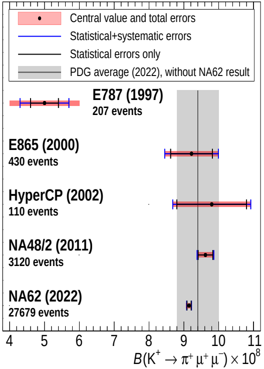
$N_{bg}^{exp} = 7.8 \pm 5.6$ events

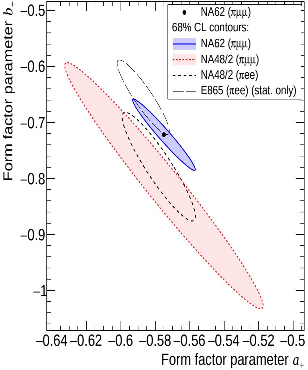
$K^+ \to \pi^+\mu^+\mu^-$: Precision measurement - result

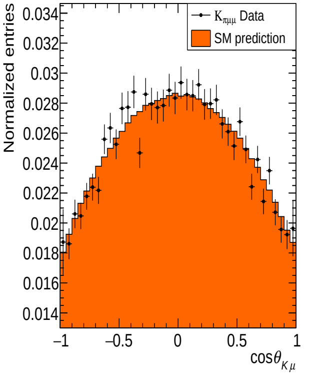
[JHEP 11(2022) 011]

$$A_{FB} = \frac{N(\cos\theta_{K\mu}>0) - N(\cos\theta_{K\mu}<0)}{N(\cos\theta_{K\mu}>0) + N(\cos\theta_{K\mu}<0)}$$

$\theta_{K\mu}$: $K\mu-$ angle in $\mu\mu$ rest frame







$B_{\pi\mu\mu} = (9.15 \pm 0.08) \times 10^{-8}$

$A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$ @68% CL

$$a_+ = -0.575 \pm 0.012_{stat} \pm 0.003_{sys} \pm 0.003_{ext}$$
$$b_+ = -0.722 \pm 0.040_{stat} \pm 0.013_{sys} \pm 0.011_{ext}$$

$K^+ \to \pi^+\gamma\gamma$: Overview

- Long-distance dominated radiative decay
- Crucial test of Chiral Perturbation Theory
- Kinematic variables (q_i : photon momenta, p: kaon momentum):

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}, \quad y = \frac{p\cdot(q_1-q_2)}{m_K^2}$$

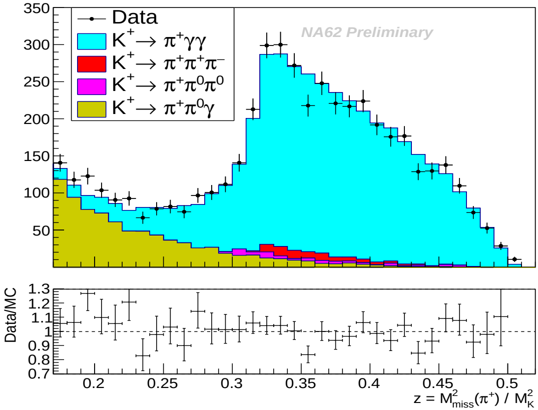
- Differential decay width: *[PLB 386 (1996) 403]*

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A(\hat{c},y,z)+B(z)|^2+|C(z)|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2|B(z)|^2\right]$$

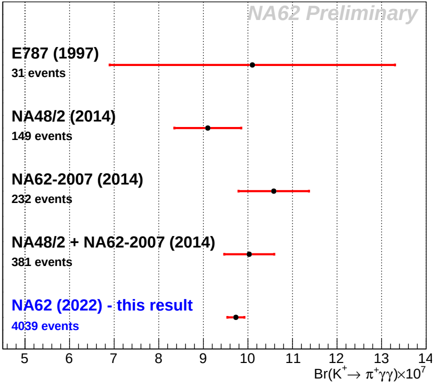
  - The spectrum and rate depend on one parameter $\hat{c}$
  - $B(z)$ appears at ChPT $\mathcal{O}(p^6)$
  - **Goal:** measure $\hat{c}$ and the corresponding branching fraction
- **Analysis of Run1 data:**
  - Signal selection: π^+ track matching K^+ track;
    EM calorimeter γ pair; $z = (P_K - P_\pi)^2/M_K^2$
  - Normalization: $K^+ \to \pi^+\pi^0$

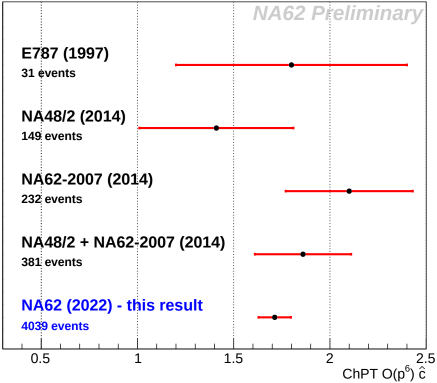
$K^+ \to \pi^+\gamma\gamma$: Precision measurement

- $K^+ \to \pi^+\gamma\gamma$ signal sample, $z > 0.25$:
  - 4039 events observed with expected background: 393 ± 20 events
  - Main source of bkg.: $K^+ \to \pi^+\pi^0\gamma$
- Fit procedure:
  - MC reweighed for different values of $\hat{c}$, performed maximum likelihood fit



$K^+ \to \pi^+\gamma\gamma$: *Preliminary result*





Preliminary results:

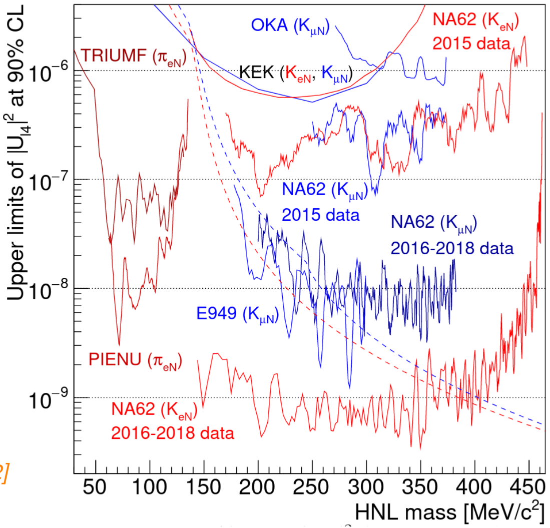
$$\mathrm{BR}(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.19) \times 10^{-7}$$

$$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{sys} \mathcal{O}(p^6)$$

- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to 350 MeV.

  [NPB 590 (2000) 562]
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, and extended the HNL mass range to 384 MeV.
- New upper limit at 90% CL: $\mathrm{BR}(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$. Similar limits on $\mathrm{BR}(K^+ \to \mu^+ \nu X)$, with $X =$ invisible.

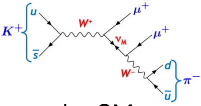
  [Theory: PRL 124 (2020) 041802]
- Full Run 1 data set.



[Phys. Lett. B 816 (2021) 136259]

NP searches in kaon decays

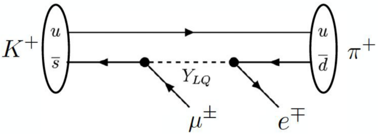
- Search for Majorana neutrinos in LNV $K^+ \to \pi^- \ell^+ \ell^+$ decays
  [Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]]



  - DM + Baryon Asymmetry + low mass of SM ν
    can be explained by adding three sterile Majorana neutrinos to the SM
  - Searches for LNV in 3-track decays:
    - LNV decays improving over PDG limits:

$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ @90% CL
$\mathrm{BR}(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ @90% CL *[PLB 830 (2022) 137172]*
$\mathrm{BR}(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ @90% CL *[PLB 797 (2019) 134794]*
$\mathrm{BR}(K^+ \mu^+ \nu e^+ e^+) < 8.1 \times 10^{-11}$ @90% CL *[PLB 838 (2022) 137679]*

- Search for LNV/LFV in $K^+ \to \pi \mu e$ decays
  - Experimental signature:
    3 charged tracks with $\pi^\pm \mu^\mp e^+$
  - BR measured relative to
    normalization channel $K^+ \to \pi^+ \pi^+ \pi^-$



$\mathrm{BR}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$

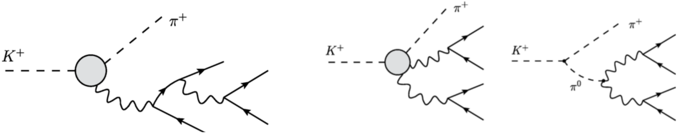
$\mathrm{BR}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$

$\mathrm{BR}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$ *[PRL 127 (2021) 131802]*

1 order of magnitude improvements compared to previous searches. Upper limits at 90% CL.

$K^+ \to \pi^+ e^+ e^- e^+ e^-$ $(K_{\pi 4e})$

- **Theory:**
  - SM allowed BR$= 7.2 \pm 0.7 \times 10^{-11}$ (outside π^0 pole)



$K^+ \to \pi^+ \gamma^*$ $K^+ \to \pi^+ \gamma^* \gamma^*$ $K^+ \to \pi^+ \pi^{0*}$

- **Dark sector probe:** [arXiv:2012.02142]
  - $K^+ \to aa$ with $a \to e^+ e^-$ QCD axion, e.g. $m_a = 17$ MeV BR$= 1.7 \times 10^{-5}$
  - $K^+ \to \pi^+ S$, $S \to A'A'$ dark scalar and $A' \to e^+ e^-$ dark photon $m_S > 2m_{A'}$

- **Procedure:**

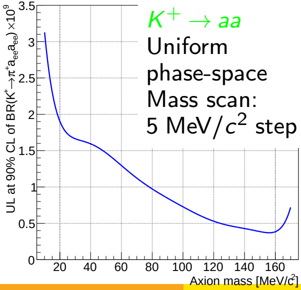
$K_{\pi 4e}$ SM:

Acceptance from MC

No candidate observed in SR

- **Result:** [PLB 846 (2023) 138193]

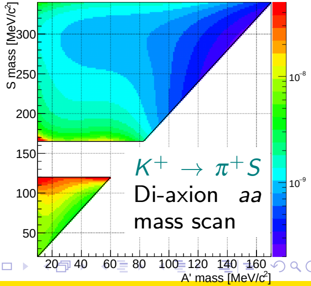
BR$(K_{\pi 4e}) < 1.4 \times 10^{-8}$ @90% CL



$K^+ \to aa$

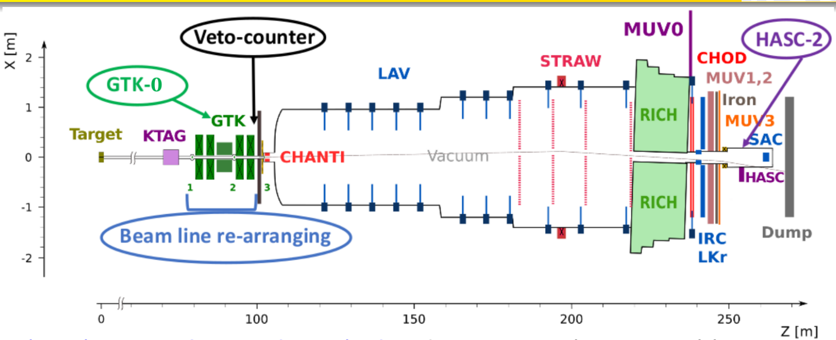
Uniform phase-space

Mass scan: 5 MeV/c^2 step



$K^+ \to \pi^+ S$

Di-axion aa mass scan

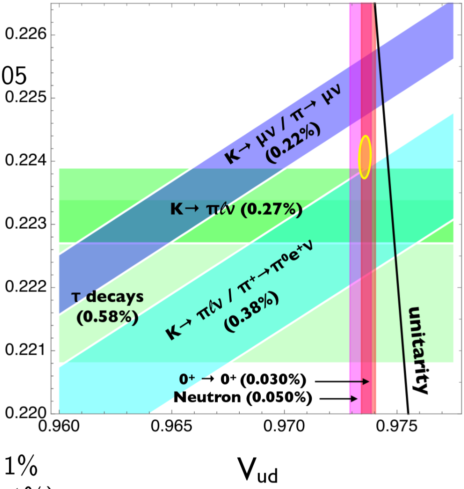


Data taking between CERN LS2 and LS3: On-going, with optimized beam intensity

- Upstream background suppression: beam line re-arranging to swipe away upstream π^+, adding a fourth Gigatracker station (GTK-0) and a new veto-counter system to detect upstream decay products
- Additional off-axis calorimeter (HASC-2) to further suppress $K_{2\pi}$ background
- **Goal:** $BR(K^+ \to \pi^+ \nu \bar{\nu})$ measurement with $\mathcal{O}(15\%)$ final precision
- Trigger upgrade to study new channels (e.g. $K^+ \to \pi^+ e^+ e^-$)
- Continuing LNV/LFV and dark sector searches with $K^+ \to \mathcal{O}(\%)$ LFUV test

Plans for V_{us}/V_{ud} Measurement

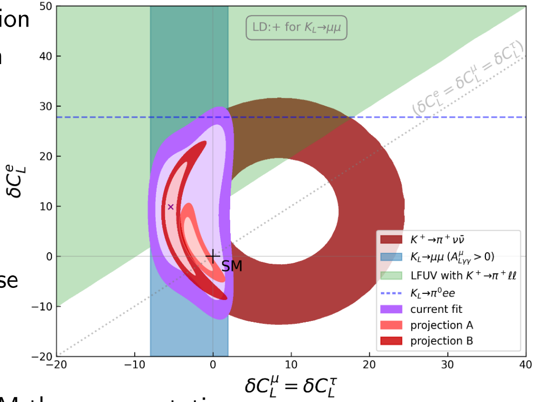
- **Potential measurement** to address the Cabibbo angle anomaly $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$
  - $R_A^{K_{\mu2}} \frac{\Gamma(K_{\mu2})}{\Gamma(\pi_{\mu2})}$, $R_A^{K_{\mu3}} \frac{\Gamma(K_{\mu3})}{\Gamma(\pi_{\mu2})}$



- **Strategy:**
  - Reconstructing decay-in-flight $\pi^+ \to \mu^+ \nu$ from $K^+ \to \pi^+ \pi^0$
  - Cancellation of several systematic uncertainties (e.g. μ PID)
  - Analysis ongoing on RUN1 data
  - Expected statistical uncertainty $< 1\%$
  - Target systematic uncertainty $\mathcal{O}(0.1\%)$
  - External uncertainty from the knowledge of BR$(K^+ \to \pi^+ \pi^0)$

- **Letter of Intent**: *[arXiv:2211.16586v1]*
  proposal to SPSC under preparation
  - K^+ and K_L physics program at CERN SPS after LS3
  - Intensity $4-6$ times higher with respect to NA62
  - Detectors with $\mathcal{O}(20\text{ ps})$ time resolution
  - Similar experimental layouts for charged and neutral phase

[arXiv:2206.14748v1]



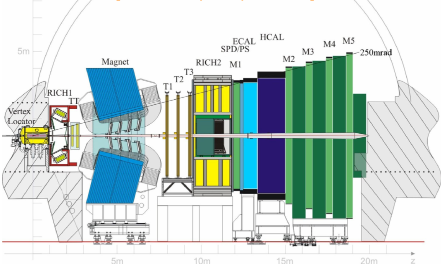
- **Physics program:**
  - $K^+\to\pi^+\nu\bar{\nu}$ approaching SM theory expectation
  - $K_L\to\pi^0\ell^+\ell^-$ observation and measurement of the BR
  - LFUV tests with precision $<1\%$
  - LFV/LNV searches with $\mathcal{O}(10^{-12})$ sensitivity
  - Measurement of V_{us} and main kaon decay modes
  - Dump physics in synergy with Shadows experiment

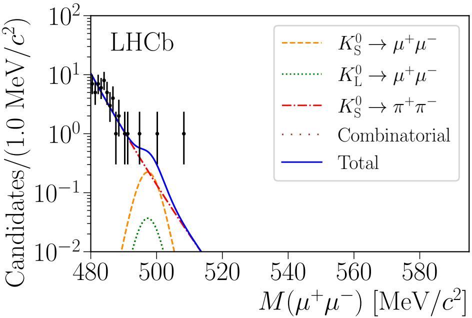
$K_S \to \mu^+\mu^-$ at LHCb

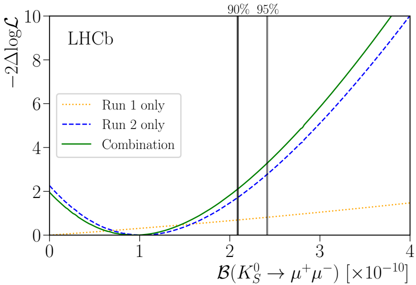
Data samples:

- **Run 1:** 3fb^{-1} (2011-12 data) at 7-8 TeV
- **Run 2:** 5.6fb^{-1} (2016-18 data) at 13 TeV

[PRL 125 (2020) 231801]







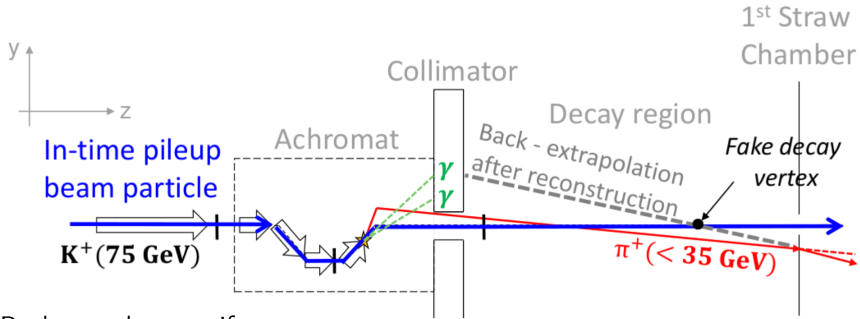
Run1+Run2 result:
BR($K_S \to \mu^+\mu^-$) $< 2.1 \times 10^{-10}$ **(90% CL)**

Conclusion

- **NA62:**
  - Complete result for $K^+ \to \pi^+ \nu\bar{\nu}$ from Run 1 (2016+2017+2018):
    - observed: 20 events; expected background: ~ 7 events *[JHEP 06 (2021) 093]*
    - **BR**$(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ **at 68% CL** (3.4σ)
  - Precision measurements of rare kaon decays: *[JHEP 11(2022) 011]*
    - $K^+ \to \pi^+\mu^+\mu^-$ (LFUV) and $K^+ \to \pi^+\gamma\gamma$ (χPT)
  - BSM physics in kaon decays:
    - $K^+ \to \pi^+ e^+ e^- e^+ e^-$ analysis & $K^+ \to aa$ ($a \to e^+e^-$) interpretation *[PLB 846 (2023) 138193]*
    - searches for $K^+ \to \ell^+ N$ and $K^+ \to \mu^+ \nu X$ decays; many LNV/LFV modes *[PLB 816 (2021) 136259, NPB 590 (2000) 562]* *[PLB 830 (2022) 137172]* *[PLB 797 (2019) 134794]* *[PLB 838 (2022) 137679]* *[PRL 127 (2021) 131802]*
  - Next steps:
    - Data taking on-going with upgraded detector
    - New measurement of V_{us} with kaons
- **KOTO:**
  - Final result from 2016-18 data: BR$(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ @90% C.L.
  - Preliminary result from 2021: BR$(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$ @90% C.L.
  - Design work for a new KOTO-II experiment to reach $\mathcal{O}(100)$ events
- **Future of kaon physics at the CERN SPS:**
  - Proposal for HIKE to measure BR$(K^+ \to \pi^+ \nu\bar{\nu})$ at 5% precision and to measure BR$(K_L \to \pi^0 \ell^+ \ell^-)$ at 20% precision

Spares

Upstream background



Background source if:

- a kaon decays upstream, and only a pion enters in the decay region;
- there is an in-time pileup beam particle (in KTAG and GTK);
- the upstream generated pion enters in the decay region and is scattered in the first STRAW chamber.

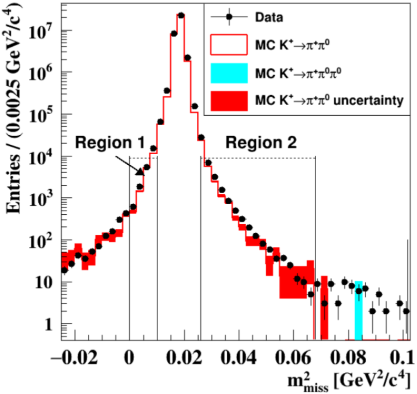
In 2018 collimator was replaced to remove early decays mechanism and data are split in subsets S1/S2 (Old/New collimator, $\sim$ 20%/80% of 2018 data). It allows to relax some cuts for S2, while keeping the S/B ratio same as for S1.

Data in *bkg* region after $\pi\nu\nu$ selection: γ-rejection applied

$$N^{exp}_{bkg}(region) = N(bkg) \cdot f^{kin}(region); \; bkg = \pi^+\pi^0 \text{ or } \mu^+\nu$$

Expected *bkg* in signal regions after $\pi\nu\nu$ selection

Fraction of *bkg* in signal region measured on control data



Background	Subset S1	Subset S2
$\mu^+\nu$	0.23 ± 0.02	0.52 ± 0.05
$\pi^+\pi^0$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0\ell^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m_{miss^2} distribution